ATTENUATION OF ELECTROMAGNETIC ACOUSTIC NOISE FROM A VARIABLE SPEED INDUCTION MOTOR BY USING DYNAMIC VIBRATION ABSORBER

by

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LIST OF ABBREVIATIONS

AC	Alternating Current
AC-RPWM	Asymmetric Carrier Random PWM
EMA	Experimental Modal Analysis
FFT	Fast Fourier Transform
FRF	Frequency Response Function
IEC	International Electrotechnical Committee
ODS	Operational Deflection Shape
PFM	Pulse Frequency Modulation
PWM	Pulse Width Modulation
PZT	Piezoelectric Insert
RPPWM	Random Position Pulse Width Modulation
SLPWM	Slope Pulse Width Modulation
THD	Total Harmonic Distortion
TMD	Tunes Mass Damper
TVA	Tuned Vibration Absorber
UMP	Unbalanced Magnetic Pull

LIST OF SYMBOLS

B	Radial air gap magnetic flux density
E	Young's Modulus
F_1	Harmonic forcing force
F_R	Radial Maxwell magnetic force
F_T	Tangential magnetic force
g	Gravitational acceleration
I	Beam second moment of inertia
k_1	Stiffness of mass m_1
k_2	Stiffness of mass m_2
l	Length of beam
m	Mass of beam
m_1	Mass of primary structure
m_2	Mass of dynamic vibration absorber (DVA)
x_1	Displacement of primary structure
x_2	Displacement of DVA
X_1	Vibration amplitude of primary structure
X_2	Vibration amplitude of DVA
$\ddot{x}_1$	Acceleration of primary structure
$\ddot{x}_2$	Acceleration of DVA
μ_0	Air gap magnetic permeability
ω_n	Harmonic forcing force frequency
ω_1	Natural frequency of primary structure
ω_2	Natural frequency of DVA

PENGURANGAN HINGAR AKUSTIK ELEKTROMAGNETIK DARIPADA MOTOR INDUKSI KELAJUAN BOLEH UBAH DENGAN MENGGUNAKAN PENYERAP GETARAN DINAMIK

ABSTRAK

Hingar akustik elektromagnetik mempunyai ciri ton hingar yang dihasilkan oleh motor induksi kelajuan boleh ubah mewujudkan suasana yang tidak selesa kepada pengendali mesin. Hingar yang berlaku pada frekuensi tinggi ini kebiasaannya berlakupada gandaan frekuensi pensuisan pada pembalik. Penyelesaian masalah hingar ini pada umumnya dicapai dengan rekabentuk elektromekanikal dan modulasi lebar denyut untuk membasmi harmonik yang menyebabkan hingar. Penggunaan penyerap getaran dinamik adalah antara alternatif yang dikaji di dalam penyelidikan ini. Ujian spektrum menunjukan bahawa daya tindakan elektromagnetik mempengaruhi secara langsung hingar elektromagnetik yang dihasilkan oleh motor induksi. Gandaan harmonik 3 kHz pada spektrum modulasi lebar denyut berlaku juga pada spektrum getaran permukaan dan spektrum hingar. Analisis mod dan ujian spektrum menunjukan bahawa hingar dengan frekuensi 6 kHz pada kelajuan 1250 rpm dan ke bawah adalah disebabkan oleh getaran paksa. Pada halaju di atas 1250 rpm, hingar 3 kHz adalah disebabkan resonans. Bolt M6 sepanjang 20 mm digunakan sebagai penyerap getaran dinamik dan dipasang pada permukaan motor untuk mengurangkan hingar pada 6 kHz. Penyerap getaran dinamik menyerap getaran sebanyak 20% hingga 86%pada permukaan motor dan pengurangan aras tekanan bunyi sebanyak 12 dB(A) dapat dicapai. Ia juga berkesan pada lokasi lain pada motor dan juga pada semua kelajuan operasi. Penyerap getaran dinamik telah terbukti untuk mengurangkan hingar elektromagnetik daripada motor induksi kelajuan boleh ubah.

ATTENUATION OF ELECTROMAGNETIC ACOUSTIC NOISE FROM A VARIABLE SPEED INDUCTION MOTOR BY USING DYNAMIC VIBRATION ABSORBER

ABSTRACT

Tonal electromagnetic acoustic noise radiated from variable speed induction motor can be annoying to human operator. Occurring at high frequency, it often occurs at multiples of the inverter switching frequency. Solutions for the noise attenuation have been generally by means of electromechanical design and pulse width modulation (PWM) strategy to remove harmonics leading to noise generation. Dynamic vibration absorber (DVA) as an alternative solution was implemented in this research. Spectral test revealed that the input electromagnetic excitation has direct influence on the radiated electromagnetic acoustic noise from the induction motor. The multiples of 3 kHz harmonics in PWM spectrum was also present in the surface vibration and sound pressure spectrum. From experimental modal analysis and spectral test, it was found that the 6 kHz acoustic noise was due to forced vibration for speed of 1250 rpm and below. While at above 1250 rpm, the 3 kHz noise was due to resonance. A 20mm M6 bolt was used as DVA and attached to a point on the motor housing for targeted noise attenuation at 6 kHz. The DVA was able to absorb the surface vibration in the range of 20 to 86% and maximum sound pressure level reduction of 12 dB (A) was achieved. It was also effective at other locations on motor as well as at different operating speed. The DVA was thus proven to be a feasible method for electromagnetic noise attenuation in induction motor.

CHAPTER 1

INTRODUCTION

1.1 Overview

Induction motor is the most widely used motor for industrial applications (Sahay and Pathak, 2006). It is generally used to drive pumps, compressors, conveyor belts and fans. Apart from being low cost, its popularity is also due to its ruggedness and excellent reliability in various operating conditions. Figure 1.1 shows the construction of an induction motor. The main components of the induction motor that are responsible for torque generation are the cage rotor and stator.

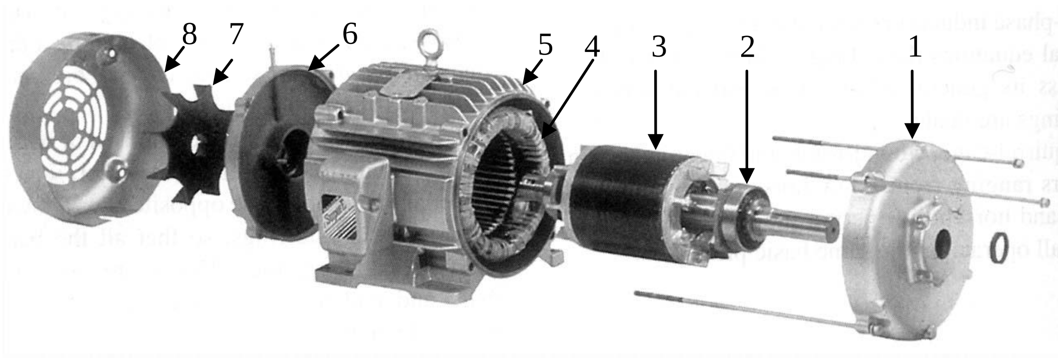

Figure 1.1 Exploded view of an induction motor. (1-Front end shield, 2 - Bearing, 3 – Cage rotor, 4 - Stator, 5 – Housing, 6 – Rear end shield 7- Cooling Fan, 8- Fan Cowl) (Wildi, 2002)

The induction motor produces its motion from the interaction of magnetic fields from both rotor and stator. Alternating current (AC) power supply to the stator coils produces rotating magnetic field around the stator. A second rotating magnetic field is then induced on the rotor bars of the squirrel cage. This two opposing magnetic field subsequently leads to the rotor's motion. Improving the advantage of the induction further for industrial use is the variable speed operation capability.

Using an inverter, the voltage and frequency of AC power supply can be controlled and thus a precise regulation of speed and torque is achieved.

While the induction motor is able to provide excellent motion drive, it has been known to produce acoustic noise which can be annoying to human exposure. The acoustic noise being emitted by an induction motor can be classified into three main categories: aerodynamic noise, mechanical noise and electromagnetic noise. Three different types of acoustic noise and its source are summarized in Table 1.1.

Table 1.1 Various types and source of acoustic noise from a variable speed induction motor (Gieras et al., 2005)

Type	**Source**	**Noise Characteristics**
Aerodynamic	Cooling fan airflow	Broadband
Mechanical	Ball bearing defects Bent shaft Rotor unbalance Shaft misalignment	Tonal
Electromagnetic	Electromagnetic force harmonics Phase unbalance Slotting effects Magnetic saturation Unbalanced magnetic pull	Tonal

All these three different types of noise source combines to produce overall sound pressure level emitted by the motor. In aerodynamic noise, air turbulence induced by the cooling fan interacts with the motor housing to create flow induced noise. With increasing motor speed, the aerodynamic noise also increases. Mechanical noise occurs at discrete frequencies and depends on the motor speed as well. Unlike the aerodynamic and mechanical noise, there are many sources that lead to the electromagnetic noise. These different sources lead to numerous harmonics in the air gap flux density between rotor and stator. This in turn leads to periodic fluctuations radial magnetic forces which deforms the stator. The radial deformation is what leads to the electromagnetic acoustic noise (Gieras et al., 2005).

The electromagnetic noise emanating from inverter driven induction motor is generally a high frequency acoustic noise. This unpleasant high frequency noise is narrow band or tonal in nature. Unlike the broadband noise in which the acoustic spectrum is spread over a range of frequency, the tonal noise generally occurs at discrete frequencies. Psychoacoustics research has indicated that tonal acoustic noise is subjectively more annoying than broadband noise (Kryter, 1968). Typical electromagnetic acoustic noise from a variable speed induction motor occurs at frequencies from 1000 Hz to 20,000 Hz. These frequencies are generally multiples or harmonics of various design parameters of the induction motor such as inverter switching frequency, number of stator and rotor slots and line frequency. Although human hearing ranges from 200 Hz to 20,000 Hz, human ears are more sensitive to the frequency range between 1000 Hz and 5000Hz (May, 2000). Realizing the sensitivity at this region, narrow frequency bands of electromagnetic noise within and nearby this frequency range is to be avoided. Generally, the aerodynamic and mechanical noise will mask the electromagnetic noise. However in certain cases, the electromagnetic acoustic noise can be the most dominant source of noise. For example, electromagnetic acoustic noise is more perceivable in light rail vehicle with traction motor (Le Besnerais et al., 2009a). Thus, the solution for electromagnetic acoustic noise is crucial.

The research and development in electric motor noise abatement was largely driven by strict industrial regulations throughout the world. Realizing that acoustic noise is one of the occupational health hazard, the motor noise limit is regulated by International Electrotechnical Commission (IEC). Figure 1.2 shows the standards for maximum permissible sound power levels for a IEC squirrel cage induction motor. The noise limit is based on the rated power output and number of poles.

Rated speed n_N (rev/min)	$n_N \leqslant 960$			$960 < n_N \leqslant 1320$			$1320 < n_N \leqslant 1900$			$1900 < n_N \leqslant 2360$			$2360 < n_N \leqslant 3$		
Methods of cooling (simplified code)[b]	IC01 IC11 IC21	IC411 IC511 IC811	IC31 IC71W IC81W	IC01 IC11 IC21	IC411 IC511 IC811	IC31 IC71W IC81W	IC01 IC11 IC21	IC411 IC511 IC811	IC31 IC71W IC81W	IC01 IC11 IC21	IC411 IC511 IC811	IC31 IC71W IC81W	IC01 IC11 IC21	IC411 IC511 IC811	I IC IC
		IC8A1W7			IC8A1W7			IC8A1W7			IC8A1W7				IC8.
	c	d	d	c	d	d	c	d	d	c	d	d	c	d	
Rated output P_N(kW or kVA)	Maximum permissible sound power level L_{WA} (dB)														
$1 \leqslant P_N \leqslant 1.1$	73	73		76	76		77	78		79	81		81	84	
$1.1 < P_N \leqslant 2.2$	74	74		78	78		81	82		83	85		85	88	
$2.2 < P_N \leqslant 5.5$	77	78		81	82		85	86		86	90		89	93	

Figure 1.2 Maximum permissible Sound Power Levels in Decibels for IEC Squirrel Cage Induction motors (Toliyat and Kliman, 2004)

Solutions for electromagnetic noise mitigation for variable speed induction motor can be generally divided into two main methods: electromechanical design and pulse width modulation (PWM) strategy. The electromechanical design solution looks into the various geometrical design parameters of the induction motor. Examples include rotor-stator slot number combination (Kobayashi et al., 1997), stator slot opening width (Le Besnerais., 2009b) and rotor skew angle (Nau, 1997). This parameter has to be taken into account at the early stage of the design before manufacturing the motor. In PWM strategy, the PWM waveform from the inverter is optimized such that time harmonics of the magnetic flux density is minimized (Timar and Lai, 1994). Examples include ultrasonic switching (Gilliam et al., 1988), random PWM (Habetler and Divan, 1991) and pulse frequency modulation (PFM) (Ertan and Simsir, 2004).

Structural modification as a method to attenuate annoying acoustic noise has a potential to reduce the electromagnetic noise as well. In structural modifications, the vibration response of the structure can be altered by shifting the resonance or changing the dynamic performance parameters. Various methods for structural modifications include mass modifications, selection of materials, stiffness alteration and vibration absorber addition (Kundra and Nakra, 1997). Structural modification as means to mitigate noise has been investigated for gearbox housing noise (Inoue et al., 2002) and drum brake squeal (Hamid et al., 2013).

In this research, the use of dynamic vibration absorber (DVA) to attenuate electromagnetic noise is investigated. DVA is a passive vibration control method whereby a secondary mass attached to a troublesome primary mass. The secondary mass natural frequency needs to be similar to the frequency of force excitation in order for primary mass vibration reduction (Mehta, 2012). The reduction should lead to reduction of the noise as well. DVA application has been popularly used for vibration control and the only reported use for acoustics control has been for aircraft cabin noise (von Flotow, 2000). It has not been reported to be used for noise control of electric motor and it is thus worth investigating on an induction motor in this research.

1.2 Problem Statement

Solutions for electromagnetic noise for induction motor have been largely focused on electromechanical design and PWM strategy. Various possibilities to optimize this two methods have reached its limit due to a range of tradeoffs such as sacrificing electrical efficiency and manufacturing costs. Moreover, there is a limit to the maximum noise level reduction achievable by each method. DVA as an alternative means to mitigate the electromagnetic acoustic noise is thus evaluated.

1.3 Motivation

Due to the electrical nature of the electromagnetic noise generation, the solution for electromagnetic noise has been tackled from electrical engineering point of view. The current solutions available revolve around controlling the source of harmonics in the magnetic field between rotor and stator. From mechanical engineering standpoint, the electromagnetic noise problem can be solved by applying the solution at the receiver end by attaching a DVA on the motor to absorb and reduce the surface vibration that leads to acoustic noise. This research work is thus motivated by the need to solve the problem in an alternative way.

1.4 Objective

The main objective of this research is to evaluate the effectiveness of DVA to suppress tonal electromagnetic acoustic noise from variable speed induction motor

1.5 Contributions

The first contribution of this research is to investigate the correlation between the input electromagnetic excitation and the radiated electromagnetic acoustic noise. Though literature had mentioned that the frequency content of PWM has influence on the acoustic noise, but there is no available experimental data to show clearly the causal relationship. Through various noise and vibration characterization, this research thus shows the causal relationship between the input electromagnetic excitation and output electromagnetic acoustic noise.

The second and most important contribution is the investigation into the feasibility of DVA to suppress electromagnetic acoustic noise. The precedence of electromechanical design and PWM strategy has narrowed the scope for electromagnetic acoustic noise solution by various researchers. This research thus investigated an alternative solution.

1.6 Scope

The research is limited to experiments on motor noise and vibration characterization and DVA implementation. Basic noise and vibration characterization experiments such as spectral test, modal analysis and ODS was performed. PWM waveform tracing to determine the frequency content of electromagnetic excitation was conducted. Prior to DVA implementation, modal analysis on candidate DVA was carried out to obtain the suitable DVA. During implementation, effectiveness of DVA at various location, axis and speed was investigated.

1.7 Outline

This thesis is divided into five chapters which are introduction, literature review, methodology, results and discussions and conclusions. Chapter one presents basic idea of this research. A brief introduction to induction motor and electromagnetic noise is introduced. Problem statements, motivation, objectives, contributions, scope and outline are stated. Chapter two examines further into the literature on the electromagnetic noise generation mechanism and various solutions for noise suppression method. This chapter also presents the theory of DVA. Chapter three reports the methodology for various experiments for noise and vibration characterization and also implementation of DVA on the motor structure. In chapter four, results from the characterization and DVA implementation is presented. Finally, chapter five concludes all the findings from this research.